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(54) AN X AND GAMMA RADIATION COLLIMATOR AND METHOD OF MANUFACTURING SUCH COLLIMATOR

(71) We, GALILEO ELECTRO-OPTICS CORP., Galileo Park, Sturbridge, Massachusetts, United States of America, a corporation organised and existing under the Laws of the State of Delaware, United States of America, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates to an X and gamma radiation collimator and method of manufacturing such collimators.

In the field of instrumentation for use in nuclear physics and nuclear medicine there is a requirement for collimators for X and gamma radiation.

It is well known in the prior art to provide a collimator for X or gamma radiation which is fabricated from an assembly of lead (or other high-Z metal) strips arranged in a corrugated configuration with passageways or channels ranging in cross-section from a few millimetres to a few centimeters. In such collimators, the inter-channel septa (i.e. the lead strips) may be of the order of one millimetre in thickness and a few millimetres in width. The collimator may alternatively have an "egg-box" configuration with inter-locking septa providing rectangular cross-section channels.

The radiographic image detail which may be resolved using such collimators is limited by the centre-to-centre separation between the channels, and also, by the solid angles defined by the channel entrances and exits. As a further limitation, the septa must be of sufficient depth in the direction of propagation and thickness transverse to the direction of propagation so that substantially all the uncollimated radiation which enters the entrance face of the collimator is absorbed before reaching the exit face. Since the total fraction of radiation transmitted by such collimators varies approximately in an inverse square manner with the depth of the septa, the septa are normally fabricated from lead or some other strongly absorbing, high atomic number material. Lead is most often used because of its relatively low cost although the softness of lead places substantial limits on the minimum septa thickness, and, in turn, the minimum channel separation.

An alternative collimation technique uses a lead block with an array of circular cross-section channels drilled therein. However, the prior art collimators of these types have been limited to channels having approximately 10 square millimetre cross-sections with 0.5 millimetre inter-channel spacing. Due to the softness of lead, higher channel density results in collapse of inter-channel walls.

As a result of recent investigations in the x-ray collimation techniques, an assembly of glass channel mosaics have been considered as still another alternative form of x-ray collimators. Such channel mosaics have been previously used in electron-multipliers for image tubes. In that field, the electron-multiplying glass commonly contains significant fractions of lead oxide. In addition, such glass mosaics can have channels of the order of a few microns in diameter. However, collimators which are manufactured of these lead-glass multiple channel mosaic assemblies are only effective in the collimation of low energy radiation having wavelengths greater than 1.0 Angstrom, primarily because the proportion of lead by volume is only about 15% in glass formulations suited to the fabrication of channel mosaics. This limitation is especially significant in the field of nuclear medicine since the bulk of current diagnostic radiology requires collimated high energy radiation having a wavelength of the order of 0.15 Angstroms and smaller.

The present invention consists in a collimator for X and gamma radiation com-

prising a glass mosaic substrate made up of a plurality of elongated elements, each of said elements having a substantially uniform cross-section channel extending along its longitudinal axis, and substantially uniform thickness electrolytically plated high-Z metal coating on the surface of said substrate bounding each said channel.

The present invention also consists in a method for fabricating a multiple channel X and gamma radiation collimator having a plurality of parallel channels from a multiple element glass mosaic substrate made up of a plurality of parallel aligned etchable core columns, said columns having high-Z metal compounds dispersed therein, wherein the method comprises the steps of: etching the core of each of said columns to form said channels; establishing a conductive layer on the surface of said substrate bounding said channels, and electrolytically plating said conductive layer with a high-Z metal.

In the present invention the expression "high-Z metal" means a metal having an atomic number of at least 47.

The present invention is intended to provide a high resolution collimator for X and gamma radiation and to provide a collimator for collimating radiation of wavelength 0.15 Angstroms and smaller.

In accordance with the present invention, a collimator for X and gamma radiation may be provided by a micro-channel glass substrate having an electrolytically deposited coating of a high-Z metal on the substrate surfaces which bound the channels. The glass substrate may include a substantial fraction of high-Z metal compounds uniformly dispersed throughout, but generally speaking, the substrate has a lower absorption coefficient than that of the high-Z metal coating along the channels. The metal coating along the channels absorbs radiation which is incident thereon and the substrate absorbs photons entering directly into the substrate from the radiation source. As a result, the composite structure is substantially more resistant to septal penetration than a similarly dimensioned collimator with the same channel diameter constructed from the substrate glass alone. Furthermore, the two components, the substrate and the coating, can be matched to different spectral ranges in order to provide a broad-band radiation collimator.

The collimator of the invention may be fabricated from a glass mosaic substrate assembly having hexagonal shaped columns with etchable cores. Initially, the cores are etched to form the collimation channels. The substrate block is then subjected to an electroless metal plating process to establish an electrically conductive layer on the substrate surface. The electroless metal plated substrate is then placed in a suitable bath and a high-Z metal is electrolytically deposited on the plated substrate surfaces with a substantially uniform thickness.

Embodiments of the invention will now be described, by way of example, with reference to the accompanying drawings, in which:

Figure 1 shows a cross-sectional view of a multiple column square channel collimator in accordance with the present invention,

Figure 2 shows a cross-sectional view of a single column of the embodiment of Figure 1,

Figure 3 shows a cross-sectional view of a multiple column hexagonal channel collimator in accordance with the present invention,

Figure 4 shows a cross-sectional view of a single column of the embodiment of Figure 3, and

Figure 5 shows, in block diagram form, the method of fabrication for the embodiment of Figure 3.

In one embodiment of the present invention, as shown in Figures 1 and 2, a collimator comprises a plurality of columns having square cross-section channels with the columns arranged in a mosaic configuration so that their longitudinal axes are parallel. The core of the representative square glass column 10 has been etched to provide a substrate section having a channel 12 extending lengthwise along the column's central longitudinal axis. The interior surface of column 10 is coated with high-Z metal plating 14. It will be understood that a relatively thin electrically conductive material (not shown in Figures 1 and 2) may be disposed between the plating 14 and the surface of column 10. The thickness of the substrate section of column 10 is denoted t_s , the thickness of the high-Z metal plating is denoted t_p , and the distance between opposite interior faces of the square column is denoted as d . In addition, the length of the column is hereafter denoted L .

With this geometry, three transmission fractions of incident radiation may be compared: the collimated fraction F_c (the fraction of incident radiation which passes entirely within the channels), the septal penetration fraction F_p (the fraction which passes completely through one or more septa (channel walls) of the collimator) and

the substrate transmission fraction F_s (the fraction which passes through the collimator travelling entirely within the substrate).

For the case where the radioactive source is confined to the unity solid angle

$$\left(\frac{1}{2\pi} \right)$$

of the complete hemisphere) when seen from the far-side of the collimator, the collimated fraction is equal to the solid angle offered by a channel:

$$F_c = \frac{d^2}{T^2} \quad (1)$$

The septal penetration fraction, F_p , is approximately equal to the portion which would pass through a sandwich plate composed of two layers: one layer of substrate material, and one of plating material, each layer having a thickness equal to the fraction of the total collimator volume which the corresponding material occupies. As a result, the fraction F_p may be expressed as:

$$F_p = \exp \left\{ \frac{-T [(d+2t_p+2t_s)^2 \mu_s + (d+2t_p)^2 (\mu_p - \mu_s) - d^2 \mu_p]}{(d+2t_p+2t_s)^2} \right\} \quad (2)$$

The substrate transmission fraction is the product of the solid angle presented by the substrate and its attenuation within the substrate:

$$F_s = \frac{2t_s}{T} e^{-\mu_s T} \quad (3)$$

since the sheet form of the substrate medium sandwiched between two plating layers leads to a cylindrical solid angle equal to $2t_s/T$.

In the present embodiment configured for the collimation of radiation with energy less than 100 KeV, each column is composed of a lead-glass substrate, such as Type 8161 manufactured by Corning Glass Works, Corning, New York. This glass has an absorption coefficient $\mu_s = 3.72$ for 85 KeV radiation (with corresponding wavelength 0.146 Angstroms).

Glass substrates with lead dispersed throughout may be used in embodiments of the present invention for radiation with energy as high as 200 KeV. However, for radiation with energy less than 85 KeV, Barium-Lanthanum glass, such as described in U.S. Patent No. 3,508,764, is preferred.

In the presently described embodiment, the dimensions of the structure appearing in Figure 2 have the following values:

$$\begin{aligned} T &= 16 \text{ mm} \\ t_s &= 0.0025 \text{ cm} \\ t_p &= 0.0075 \text{ cm} \\ d &= 0.060 \text{ cm} \end{aligned}$$

In other collimator embodiments according to the present invention, the centre-to-centre channel spacing may lie in the range 0.03—0.1 cm, channel length in the range 10—30 mm, channel cross-sectional area in the range 0.001—0.01 cm² and ratio of the high-Z channel coating thickness to the column wall thickness (t_p/t_s) in the range 5:1 to 10:1.

In the present embodiment, the high-Z metal plating is Cadmium which has an absorption coefficient $\mu_p = 20$ for 85 KeV radiation. In other embodiments, the high-Z metal plating may comprise lead, tin, tantalum, gold, platinum, tungsten, barium or lanthanum.

For this structure, the fraction F_c , F_p and F_s may be expressed as follows for 85 KeV radiation:

With these values, the overall signal-to-noise ratio S/N may be expressed as:

$$\begin{aligned} F_c &= 1/470 \\ F_p &= 1/6714 \\ F_s &= 1/22576 \end{aligned}$$

With these values, the overall signal-to-noise ratio S/N may be expressed as:

$$S/N = \frac{F_c}{F_p + F_s} = 11$$

Thus, for radiation of energy in the range less than 100 KeV collimated using this configuration with cadmium plating on a Type 8161 glass micro-channel substrate, a signal-to-noise ratio of the order of 11 to 1 may be achieved.

Figure 3 shows a collimator configuration which is similar to the embodiment of Figure 1, but where the cross-section of each mosaic column is hexagonal. As shown in Figure 4, the distance between opposing faces of the interior surfaces of each column is denoted by the reference letter d' . The elements of the structure of Figure 4 which correspond to similar elements in Figure 2 are denoted by identical reference numerals. Although, the hexagonal geometry of the embodiment of Figures 3 and 4 is somewhat more complex than the square geometry of the embodiment of Figures 1 and 2 leading to correspondingly more complex expressions for the F_c , F_p and F_s , the fractions are substantially similar for the hexagonal structure, particularly since the cross-section area of the hexagonal channel is approximately equal to 90% of the corresponding area of the square channel for $d'=d$.

The hexagonal column collimator provides three advantages compared with the square column collimator:

- (1) the hexagonal element mosaic as a whole is structurally more stable due to the interlocking of the columns,
- (2) the hexagonal elements are individually more resistant to collapse, permitting thinner column walls for a given substrate mass and smaller centre-to-centre separation of columns, and
- (3) the angles which permit the transmission of incident radiation wholly within the glass substrate are greatly curtailed.

The embodiment of Figures 3 and 4 may be fabricated by the following procedure (shown in Figure 5 in block diagram form) for a 6.4 cm×6.4 cm×10.2 cm glass block comprising a hexagonal column mosaic with 800 micron centre-to-centre spacing. The multiple channel mosaic substrate is formed by first drawing hexagonal columns having etchable cores, fusing the columns and cutting to a desired length (16 mm) to form a 6.4 cm×6.4×16 mm mosaic structure, and then etching cores, using procedures well known in the art, for example, as taught by U.S. Patent No. 3,294,504 to Hicks, assigned to the assignee of the present invention. For this preferred embodiment, the etch resistant portion of the columns is composed of Type 8161 lead glass having 14% by volume lead oxide, manufactured by Corning Glass Works, Corning, New York.

The substrate is etched to form the channels by immersion into an etch solution of 10% hydrobromic acid at a temperature in the range 75—80° Fahrenheit. The substrate is kept in the etch solution until the column cores are completely etched, although the etch solution may be changed during the etching to maintain a controlled rate of etch. After etching, the sample is thoroughly rinsed in deionized water and dried. The substrate in etched form is generally 75% open area. The etching process is denoted by blocks 20—23 in Figure 5.

Following the etching process, the substrate is then subjected to an electroless plating process in which the surface of the entire substrate is made electrically conductive by the electroless deposition of a metal. Both nickel and copper are examples of metals which are well suited for this purpose. In other embodiments, alternative means may be used to establish a conductive layer on the substrate surface. For example, Type 8161 glass may be reduced with hydrogen at high temperature to render the glass surface layer conductive.

For the present embodiment, electroless nickel plating may be accomplished by the following sequence of steps, in each of which the substrate is disposed with its channels in a horizontal orientation. In each of the first five steps, the substrate is raised and lowered periodically within the appropriate liquid while simultaneously undergoing a reciprocating motion with a frequency of a few tens of cycles per minute and with a total excursion of a few centimetres. The steps performed on the substrate are:

1. Immerse in a detergent conditioner solution, for example, comprising 19 parts water and 1 part Type 1160 Conditioner, manufactured by Shipley Company, Inc., Newtown, Mass. for 2—5 minutes.
2. Rinse thoroughly in three distinct deionized water rinses to rid the surface of any foreign particles on the surface.
3. Immerse in a 15% solution of hydrochloric acid for about 2—5 minutes to condition the surfaces.
4. Immerse in a metallic colloidal sensitizer solution (such as a dilute colloidal palladium aqueous solution, for example, 6F Sensitizer (1/4 gram/litre) manufactured by Shipley Company, Inc., Newtown, Mass.) for 2—5 minutes for "seeding" metal particles onto the surface.
5. Rinse thoroughly in three distinct deionized water rinses to rid the surface of any loose metal particles on the surface.
6. Immerse in a metallic activator (such as a dilute stannous chloride aqueous solution, for example, Catalyst 19 (1—3 gram/litre) manufactured by Shipley Company, Inc.) which is attracted to the already sensitized substrate surfaces, for 2—5 minutes.
7. Rinse thoroughly in at least three distinct deionized water rinses to insure that no activator is carried into the electroless bath.
8. Transfer (in deionized water and in the same holder used in the preceding steps) to an electroless nickel plating bath comprising nickel chloride (30 gram/litre), sodium glycollate (50 gram/litre) and a reducing agent such as sodium hypophosphite (10 gram/litre) (adjusted to a pH of 4.0—6.0) or some other electroless nickel plating bath, such as Ni 416, manufactured by Enthone, Inc., New Haven, Connecticut. The bath is maintained at 185°—190°F and constantly stirred to avoid hot spots. The substrate is repetitively immersed in the bath using a dunking motion (at about 30 strokes/minute) for a 5—7 minute period to deposit 4—6 μ uniform film of nickel on all substrate surfaces.
9. Rinse thoroughly in deionized water using at least three distinct rinses to remove any trace of nickel salt.
10. Dry thoroughly.

The electroless process is shown in block diagram form in Figure 5 in blocks 27—36. In other embodiments, alternative electroless plating techniques may be employed.

In the present embodiment, the nickel-coated hexagonal element mosaic may then be plated with cadmium as previously described for the square-channel mosaic, if the radiation to be collimated has energies less than 100 KeV. However, for radiation energies exceeding 100 KeV, lead is preferred to cadmium because of the greater absorption coefficient of lead at the higher energy level, i.e. in the 100—200 KeV range. A layer of lead, having a thickness of from 50 μ to 200 μ , may be deposited as follows:— The nickel-plated substrate is immersed in a plating bath having a temperature in the range 70°—90°F and containing the formulation:

- 1700 ml—Lead Fluoroborate—50% solution with water, (Harstan Chemical Co., Brooklyn, New York)
- 2800 ml—water
- 75 ml—Chinol LF—3M solution (2 ounces/gal.), (manufactured by Harstan Chemical Company, Brooklyn, New York).

In lieu of the Shinol solution, an aqueous solution of peptone, gelatin or extracted bone glue may be utilized.

The lead plating is achieved with a periodic forward reverse plating cycle, with an approximately 16—24 hours duration. The forward cycle is ten minutes at a plating current density in the range 60—75 amps per square foot from an electrode in said bath to said substrate while the reverse cycle is five minutes at 25% of the plating current density from said substrate to said electrode. The lead plating process is shown in block diagram form in Figure 5 in block 38.

Using this described process for the fabrication of the collimator, a substantially uniform thickness 70 μ lead plating may be produced on the 5 micron nickel plated substrate with hexagonal lead-glass channel mosaics having 800 micron centre-to-centre spacing, and with channel lengths of the order of 15 millimetres. Taking into account the 5 μ nickel under-layers, 70 μ lead layer in each channel, and the 50 μ inter-channel substrate thickness, (each of the channel septa being 25 μ thick), a 600 μ face-to-face open channel remains with cross-sectional area approximately

0.0025 cm². With such a structure, only one part in 10⁶ of radiation in the 125 KeV range which is incident on the collimator is not absorbed by the lead plating.

It will be understood that the above-noted process is generally suitable to fabricate many embodiments of a collimator in accordance with the present invention, including embodiments having centre-to-centre channel spacing in the range 0.03—0.1 cm, channel length in the range 10—30 mm, channel cross-sectional area in the range 0.001—0.01 cm² and t_p/t_s ratio in the range 5:1 to 10:1.

WHAT WE CLAIM IS:—

1. A collimator for X and gamma radiation comprising, a glass mosaic substrate made up of a plurality of elongated elements, each of said elements having a substantially uniform cross-section channel extending along its longitudinal axis, and substantially uniform thickness electrolytically plated high-Z metal (as hereinbefore defined) coating on the surface of said substrate bounding each said channel.

2. A collimator according to claim 1 wherein said glass substrate includes high-Z metal compounds having a substantially uniform dispersion within said substrate.

3. A collimator according to claim 2 wherein said high-Z metal in the compounds dispersed within said substrate and said high-Z metal coated on said substrate is one or more of lead, tin, tantalum, cadmium, gold, platinum, tungsten, barium or lanthanum.

4. A collimator according to claim 3 wherein said substrate includes a relatively thin, substantially uniform thickness electroless deposited metallic layer on its surface bounding each said channel.

5. A collimator according to claim 4 wherein said electroless deposited metallic layer is nickel or copper.

6. A collimator according to claim 2 wherein said substrate includes a relatively thin, substantially uniform thickness electroless deposited metallic layer on its surface bounding each said channel.

7. A collimator according to claim 2 wherein each element of said mosaic substrate comprises a hexagonal cross-section column with a hexagonal channel extending along its longitudinal axis.

8. A collimator according to claim 7 wherein the centre-to-centre spacing of said columns is in the range 0.03—0.1 cm and the cross-sectional area of said channels is in the range .001—0.01 cm².

9. A collimator according to claim 8 wherein the ratio of channel coating thickness, t_p , to the thickness of said column walls, t_s , is in the range 5:1 to 10:1.

10. A collimator according to claim 9 wherein said high-Z metal in the compounds dispersed within said substrate and said high-Z metal coated on said substrate is one or more of lead, tin, tantalum, cadmium, gold, platinum, tungsten, barium or lanthanum.

11. A collimator according to claim 10 wherein said substrate includes a relatively thin, substantially uniform thickness electroless deposited metallic layer on its surface bounding each said channel.

12. A collimator according to claim 11 wherein said electroless deposited metallic layer includes a metal from the group consisting of nickel and copper.

13. A collimator according to claim 10 wherein the length of said columns is in the range 10—30 mm.

14. Method for fabricating a multiple channel X and gamma radiation collimator having a plurality of parallel channels from a multiple element glass mosaic substrate made up of a plurality of parallelly aligned etchable core columns, said columns having high-Z metal (as hereinbefore defined) compounds dispersed therein, wherein the method comprises the steps of etching the core of each of said columns to form said channels; establishing a conductive layer on the surface of said substrate bounding said channels, and electrolytically plating said conductive layer with a high-Z metal.

15. Method according to claim 14 wherein said step of establishing a conductive layer comprises the step of electroless depositing of a relatively thin, substantially uniform thickness metallic layer on the surface of said substrate bounding each said channel.

16. Method for fabricating a multiple channel X and gamma radiation collimator having a plurality of parallel channels with centre-to-centre spacing in the range 0.03—0.1 cm, length in the range 10—30 mm, and cross-sectional area in the range 0.001—0.01 cm² from a multiple element lead glass mosaic substrate made up of a plurality of parallelly aligned hexagonal cross-section, etchable core columns,

said columns having centre-to-centre spacing in the range 0.03—0.1 cm, wherein the method comprises the successive steps of:

- A. etching the core of each of said columns to form said channels by the successive sub-steps of:
 - i. immersing said substrate in a 10% hydrobromic acid solution at a temperature in the range 75°—80°F.
 - ii. rinsing said substrate in deionized water, and
 - iii. drying said substrate,
 - B. electroless plating said substrate to form a nickel plating with a thickness in the range 4—6 microns on all surfaces of said substrate by the successive steps of:
 - i. immersing said substrate in a detergent conditioner for a period in the range 2—5 minutes,
 - ii. rinsing said substrate in deionized water.
 - iii. immersing said substrate in 15% hydrochloric acid solution.
 - iv. immersing said substrate in a metallic colloidal solution for a period in the range 2—5 minutes,
 - v. rinsing said substrate in deionized water,
 - vi. immersing said substrate in a metallic activator for a period in the range 2—5 minutes,
 - vii. rinsing thoroughly in three distinct deionized water rinses,
 - viii. immersing said substrate in a uniform temperature nickel plating bath, for a period in the range 5—7 minutes,
 - ix. rinsing said substrate in deionized water,
 - x. drying said substrate and
 - C. lead plating said substrate to form a lead plating with a thickness in the range 50 microns to 200 microns on all surfaces of said substrate by:
 - immersing said substrate in a lead plating bath, and for a period in the range 16—24 hours, alternatively driving a plating current density in the range 60 to 75 amps per square foot from an electrode in said bath to said substrate for 10 minutes and driving a deplating current from said substrate to said electrode for 5 minutes, said deplating current density being 25% of said plating current density.
17. The method according to claim 16 wherein said metallic colloidal solution is a dilute colloidal palladium solution.
18. The method according to claim 16 wherein said metallic activator is a dilute stannous chloride solution.
19. The method according to claim 16 wherein said nickel plating bath includes nickel chloride, sodium glycollate, and a sodium hypophosphite reducing agent, said bath having an adjusted pH in the range 4.0—6.0.
20. The method according to claim 16 wherein said lead plating bath is maintained at a temperature in the range 70°—90°F, and has the formulation:
- 37.2% lead fluoroborate (50% water solution)
61.2% water
1.6% aqueous solution including a material from the group consisting of peptone, gelatin, and extracted bone glue.
21. A collimator for X and gamma radiation substantially as described herein with reference to and as shown in Figures 1 and 2 of the accompanying drawings.
22. A collimator for X and gamma radiation substantially as described herein with reference to and as shown in Figures 3 and 4 of the accompanying drawings.
23. A method of making a collimator for X and gamma radiation substantially as described herein with reference to Figure 5 of the accompanying drawings.

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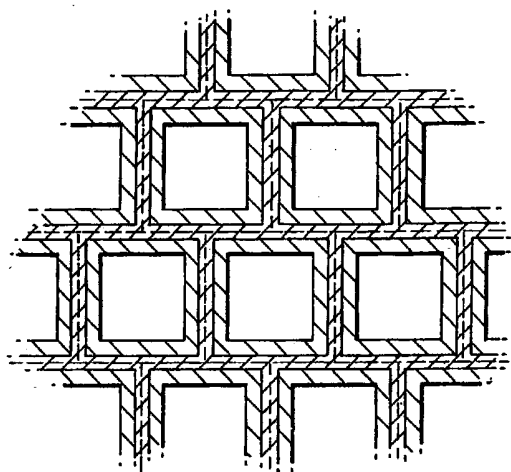


FIG. 1

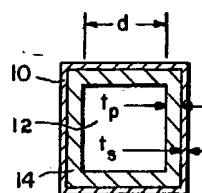


FIG. 2

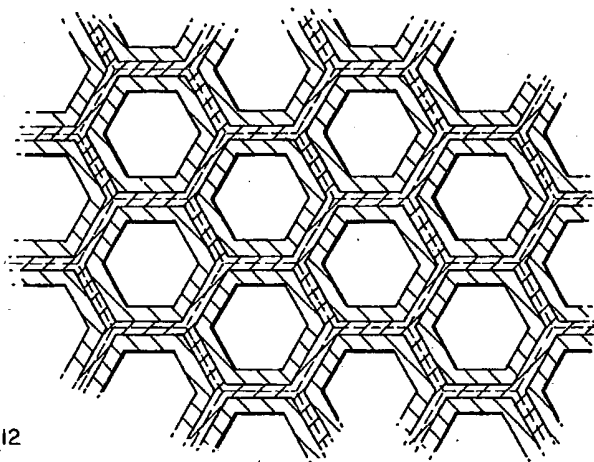


FIG. 3

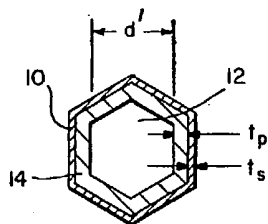


FIG. 4

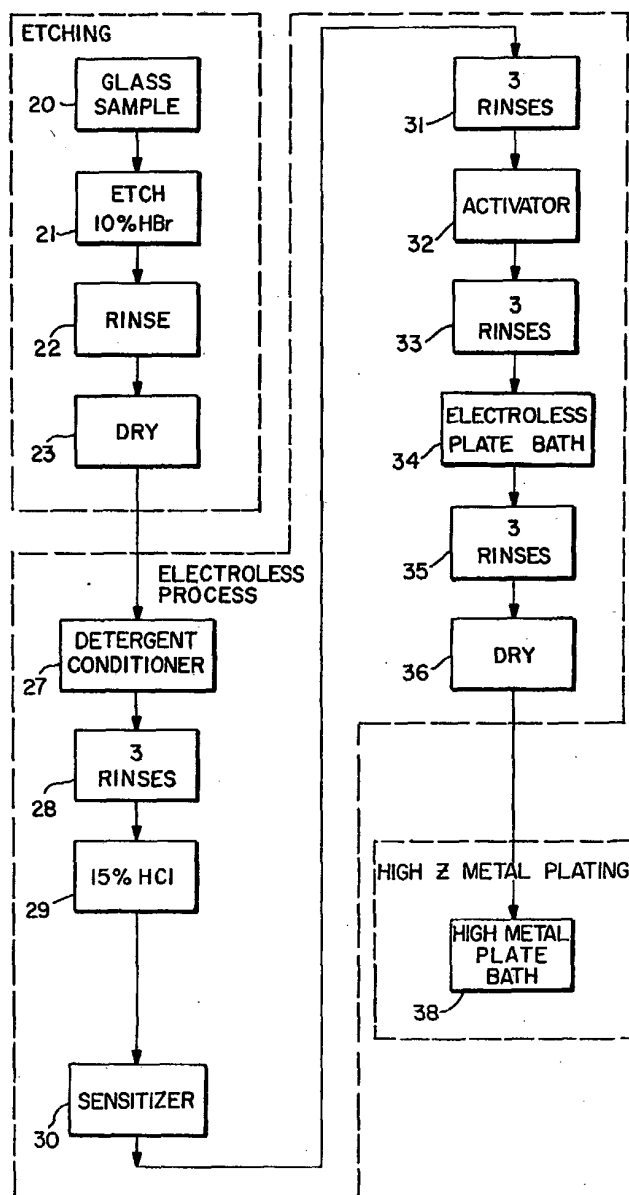


FIG. 5